

POLICY AND PROGRAM ANALYSIS

Benefits and Economic Costs of Managed Aquifer Recharge in California

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ABSTRACT

Groundwater management is important and challenging, and nowhere is this more evident than in California. Managed aquifer recharge (MAR) projects can play an important role in ensuring California manages its groundwater sustainably. Although the benefits and economic costs of surface water storage have been researched extensively, the benefits and economic costs of MAR have been little researched. Historical groundwater data are sparse or proprietary within the state, often impairing groundwater analyses. General obligation bonds from ballot propositions offer a strategic means of mining information about MAR projects, because the information is available publicly. We used bond-funding applications to identify anticipated

MAR project benefits and proposed economic costs. We then compared these costs with actual project costs collected from a survey, and identified factors that promote or limit MAR. Our analysis indicates that the median proposed economic cost for MAR projects in California is \$410 per acre-foot per year (\$0.33 per m³ per year). Increasing Water Supply, Conjunctive Use, and Flood Protection are the most common benefits reported. Additionally, the survey indicates that (1) there are many reported reasons for differences between proposed and actual costs (\$US 2015) and (2) there is one primary reason for differences between proposed recharge volumes and actual recharge volumes (AFY): availability of source water for recharge. Although there are differences between proposed and actual costs per recharge volume (\$US 2015/AFY), the ranges for proposed costs per recharge volume and actual costs per recharge volume for the projects surveyed generally agree. The two most important contributions to the success of a MAR project are Financial Support and Good Communication with Stakeholders.

KEY WORDS

California groundwater, managed aquifer recharge, water storage, groundwater recharge

INTRODUCTION

Groundwater plays a critical role in water management and drought resilience in California. Groundwater supplies almost 30% of the state's water during normal years, and this percentage increases to 40% during dry years and to nearly 60% during drought years (CDWR 2014b). Despite the importance of groundwater in California, the resource has been managed minimally at the local level without state oversight (with an exception for certain jurisdictional boundaries within the state, such as special act districts and adjudicated basins) (Nelson 2012). Unconstrained pumping of groundwater aquifers has resulted in historically low groundwater elevations in aquifers throughout the state and has led to deteriorating groundwater quality, land subsidence, and seawater intrusion (Famiglietti et al. 2011; Faunt 2009). As a result of the limited monitoring and a primary focus on local control of groundwater resources, historical groundwater data are sparse or proprietary. The California Department of Water Resources (CDWR) has identified the adverse consequences of exploiting groundwater and the limited data available for analysis and planning as major concerns (CDWR 2003).

In response to the need for better monitoring and management, California passed two critical pieces of legislation. First, the California Statewide Groundwater Elevation Monitoring (CASGEM) program was created in 2009. The main goals of CASGEM are to enhance local groundwater elevation monitoring across the state's alluvial basins and to increase data availability to the public (CDWR 2014a, 2015a). Second, the California legislature passed the Sustainable Groundwater Management Act (SGMA) of 2014 (Senate Bill 1168 [Pavley], Senate Bill 1319 [Pavley], Assembly Bill 1739 [Dickinson], California Water Code §10720–10720.9), which provides a statewide framework for local water agencies to manage their groundwater basin sustainably with limited state intervention (CDWR 2015b; WEF 2015). To meet the SGMA mandate, high and medium priority groundwater basins, as defined by the CASGEM Program, have been prioritized for the development and implementation of Groundwater Sustainability Plans (GSPs). SGMA gives Groundwater Sustainability Agencies (GSAs) the responsibility to develop and implement GSPs, with the goal of

avoiding “significant and unreasonable impacts,” by 2020 or 2022. Achieving the sustainability goals required under SGMA requires groundwater managers across the state to balance basin-wide groundwater budgets through combinations of increased groundwater recharge and reduced groundwater pumping.

Many approaches could increase the resiliency of California's groundwater system to drought events and foster local compliance with SGMA. Finding ways to recharge groundwater during wet years, so that it is available during dry periods, is one opportunity for the state to increase its resiliency and potentially mitigate some of the negative effects of past groundwater pumping. The benefits and economic costs of managed aquifer recharge (MAR) in California have been little researched (Hanak et al. 2009), yet this is important information for GSAs as they develop their GSPs. Although groundwater data are sparse or proprietary, which limits the direct assessment of MAR, the applications generated in response to the availability of proposition-defined general obligation bond funds (referred to as propositions henceforth) are available publicly. In California, proposition funding is allocated through an application process that requires detailed information about the proposed projects, such as the benefits and economic cost estimates. Thus, these propositions offer a strategic means of mining MAR information for projects within the state of California.

We mined post-2000 grant applications related to four propositions, and we used this information to answer two key questions:

1. What benefits do these facilities provide to water agencies?
2. What are the proposed costs for MAR?

To gain a better understanding of the factors affecting costs, we explored how project goals, proposition funding sources, and source water (1) influence costs and (2) vary geospatially across the state. Then, we compared proposed MAR costs with actual project costs collected via a survey instrument administered by e-mail. The survey collected information about post-project completion costs, groundwater recharge performance, and project benefits so that we could answer three additional

questions about the role of MAR in advancing water management in California:

1. How do proposed costs compare to actual costs?
2. What factors contribute to post-proposal changes to project costs or recharge volumes?
3. What factors contribute to successfully achieving project benefits?"

METHODS

Data Collection: Proposed Economic Costs and Proposed Benefits

We collected and mined proposed costs from grant applications related to four propositions: Proposition 1E, Proposition 13, Proposition 50, and Proposition 84 (Table 1). We collected data from applications accessed via online databases (https://faast.waterboards.ca.gov/Public_Interface/PublicPropSearchMain.aspx and http://www.water.ca.gov/irwm/grants/archives_p84.cfm), as well as from hard copy forms at the CDWR in Sacramento, California, when online resources were not available. Within the applications, we reviewed each project proposal and extracted data manually (Table 2). Project proposals were submitted by a variety of applicants including water districts, counties, cities,

and regional water authorities; we refer to all applicants as agencies henceforth.

We identified project benefits from proposition applications and sorted them into 11 categories: Banking Groundwater, Improving Water Quality, Flood Protection, Protecting Wetland Habitat, Increasing Water Supply, Conjunctive Use (e.g., deliberate combined use of groundwater and surface water [CDWR 2015c]), Reducing Greenhouse Gases, Reducing Imported Water, Mitigating Subsidence, Increasing Efficiency, and Creating Seawater Barrier.

A total of 338 applications were submitted under the four propositions (Table 1). Of the 190 Proposition 13 applications, only 54 were available from CDWR. Consequently, out of the 338 applications submitted to all four propositions, a total of 202 applications were available for this analysis, and 112 of the 202 applications referred to MAR projects (Table 1). Some applications—particularly those for Proposition 84—had multiple projects within one application. For our analysis, we extracted individual projects within each application, resulting in 136 projects. Thirty projects were removed because of missing information, resulting in a total sample size of 106 projects. Our analysis included projects that were both awarded and declined proposition funds.

Table 1 Information about propositions used to obtain information about MAR projects in California

Name	Description	Year	Total applications submitted	Recharge applications submitted	Recharge applications awarded	Total US\$ 2015 awarded	Recharge US\$ 2015 awarded
Prop 1E	Disaster Preparation and Flood Protection Bond Act	2006	52	19	10	\$291.9M	\$98.2M
Prop 84	Safe Drinking Water, Water Quality and Supply, Flood Control	2006	71	27	19	\$363.0M	\$197.7M
Prop 50	Water Quality Supply and Safe Drinking Program	2002	25	12	11	\$465.8M	\$260.8M
Prop 13	Groundwater Recharge and Storage	2000	190 (54) ^a	190 ^b (54) ^a	62 (15) ^c	\$316.2M	\$316.2M
Total			338 (202)	248 (112)	102 (55)	\$1.4B	\$872.9M

a. Of the 190 Proposition 13 applications, 54 were available.

b. We assumed all Proposition 13 applications had groundwater recharge components given the description of the proposition.

c. Sixty two of the 190 MAR applications were awarded; only 15 of these were available.

Table 2 Data extracted from grant applications

Data collected	Data categories
Application information	Project name County Agency Hydrologic region Groundwater basin and sub-basin
Funding information	Proposition name and year Application year Grant program Funding purpose (e.g., maintenance, construction) Application outcome (i.e., awarded or declined)
Costs	Capital costs ^a Operation and maintenance (O&M) costs Financial contributions
Source water	Surface water (i.e., diversions from streams and water bodies) Stormwater Wastewater Blend (i.e., combination of two or more of the previous categories)
Project goals	MAR as a primary goal(e.g., increase groundwater supply, groundwater banking) MAR as an ancillary goal (e.g., flood control, improve wetland habitat)
Direct recharge volume	Proposed average annual volume of water recharged (acre-feet per year)
Geospatial information	Location Hydrologic region Groundwater basin and sub-basin

a. Proposed total capital project costs included: land costs; planning, design, and engineering costs; capital costs; administration costs; environmental compliance, mitigation, and enhancement costs; construction administration costs; and contingency costs.

Accepted projects represented about 40% of our sample. Declined projects were not necessarily a reflection of a poorly-proposed project. Propositions were limited with their funding and the competition for funding was high.

We removed projects that had partial data (i.e., projects that were missing data on costs, recharge method, or source water used for recharge), with one exception: if operation and maintenance (O&M) costs were missing and the other data were available, we calculated the O&M costs under the assumption that O&M costs are a percentage of capital costs (See “[Data Analysis: Proposed and Actual Costs per Recharge Volumes](#)”). Our study focused only on infiltration and injection methods of recharge and storage. After removing samples with limitations and missing data, the sample size was reduced from 136 to 106 projects.

Each project application included information on location, as well as information about the project’s hydrologic region and groundwater basin. In some cases, the reported location did not fall within

the correct hydrologic region, groundwater basin or groundwater sub-basin. In these cases, we randomized the placement of the point within an area that satisfied the correct hydrologic region, groundwater basin and groundwater sub-basin.

Data Collection: Actual Economic Costs and Recharge Volumes and Factors Promoting and Limiting MAR Benefits

We collected actual costs using a survey instrument (Appendix A). The survey used open and closed-ended questions to confirm general project facts and goals and to obtain post-project completion costs and recharge volumes. In addition, we drafted specific questions to inquire about (1) the reasons for proposed and actual cost differences, (2) the reasons for proposed and actual groundwater recharge volume differences, (3) actual project benefits in addition to the primary project benefit documented in the application, and (4) aspects of the project that contributed to achieving the primary project benefit (Table 3). Surveys were administered to agencies with

Table 3 Specific survey questions used to inquire about the reasons for changes in actual costs and performance (if applicable), and the benefits of projects

Questions	Answer options
Which factors may have contributed to a different actual total project cost than proposed by your agency?	Feasibility study was insufficient Not enough data Water source availability changed Contingency factor was insufficient Land was more expensive to secure Environmental compliance costs were greater than anticipated Construction cost estimates were low Project time lines were extended Unsure, explain Other, explain
Which factors may have contributed to a different predicted average annual recharge volume?	Groundwater recharge was a major project priority Change in water source availability Hydrogeological conditions were different than predicted Feasibility study was conservative Adequate access to water Adequate funds to complete the project Other, explain
Has your agency seen other benefits as a result of this project?	Diversified water portfolio Enhanced regional self-sufficiency Enhanced or established ties with partner agencies Increased flexibility in water management Increased resilience to drought Increased opportunity for state funding Maintained local control Increased access for matching funds Other, explain
Which of the following aspects contributed to achieving the primary project benefit?	Financial support Good communication with stakeholders Good feasibility study Long-term data collection Regular hydrologic monitoring at project site Reliable water source availability Other, explain

projects that had been completed by August 2015. Projects funded more recently—Proposition 1E and Proposition 84—were still in-progress and did not fit the study criteria. Thirty completed projects were funded under Proposition 13 and Proposition 50, and we approached the corresponding agencies to participate in our survey. We received 13 responses out of 30 survey requests for our analysis, nine of which were from Proposition 50 and four of which were from Proposition 13.

Boundaries of Analysis: Comparisons to Surface Water Storage

Our analysis adopted similar boundaries to surface water storage cost studies. There is considerable research on the costs of surface water storage (e.g.,

CDWR 2013; Hanak et al. 2009; USDOJ et al. 2008, 2011, 2014), and we used this literature to inform our approach to identifying which costs to include in our analysis. We divided the storage costs into three phases: (1) the acquisition of water, (2) the conveyance of water to the storage facility, and (3) the storage of water at the storage facility. “Managed aquifer recharge” and “managed aquifer recharge and storage” are sometimes interchanged in the literature and it is important to note that not all of the projects within our study directly acknowledge groundwater storage as a benefit. Our study maintains comparable boundaries to annual costs per annual volume of surface water stored, but some caution should be exercised when using our values for direct comparison with annual costs per surface water storage volumes.

The acquisition of water included the infrastructure for getting water from streams, rivers, aqueducts, or storm drains and the infrastructure for treating water (i.e., treated sewage effluent). We found that economic cost analyses for surface water storage typically do not include costs associated with the water acquisition phase. To maintain consistency between our work and previous studies analyzing surface water storage costs, we did not include the costs for the water acquisition phase.

As noted earlier (Table 2), the projects that we assessed used four different types of source water: surface water (i.e., diversions from streams and water bodies), stormwater, wastewater, or a blend (i.e., a combination of two or more of the previous categories). Thus, costs to purchase water, costs for stormwater capture infrastructure, and costs for wastewater treatment facilities were removed when these items were individually listed in the application budgets. In five of the 19 stormwater applications, it was difficult to discern the difference between collection and conveyance infrastructure, because the information was not itemized in the budget. Given the trade-off between (1) removing these combined line items and under-estimating storage costs, or (2) including these combined line items and over-estimating storage costs, we chose the latter.

Data Analysis: Proposed and Actual Costs per Recharge Volumes

To calculate costs (US\$ 2015) per acre-foot per year (AFY),¹ we used each project's O&M costs, capital costs, project life, and average annual volume of water recharged. As described above, if a project was missing one or more of these datum points, we removed the project from the total sample. There was one exception: if O&M costs were missing and the other data were available, we calculated the O&M costs as a fraction of capital costs. We determined a ratio of 1:6 using the median of the ratios for projects with reported O&M and capital costs.

We performed a capital recovery analysis on the capital cost to annualize it,

$$C_A = C_C \frac{r(1+r)^l}{(1+r)^l - 1} \quad (1)$$

¹ We present our work in AFY so that it is relevant to the ongoing policy discussions in CA; we provide SI units in parenthesis.

where C_A is the annualized capital cost, C_C is the capital cost, r is the discount rate, and l is the project life.

We used an r of 6%, the same rate used by the granting agency, CDWR, in its Proposition 13 grant application (CDWR 2001). Annual O&M and annualized capital costs values were added together and divided by the average annual volume of water recharge in acre-feet to obtain an annual cost per volume. To adjust for inflation, we converted capital costs and O&M costs from their application year into 2015 United States dollars (US\$ 2015) using the Construction Cost Index published by *Engineering-News Record*; the Construction Cost Index tracks infrastructure specifically (<http://www.enr.com/economics>).

Statistical Analysis: Proposed and Actual Costs per Recharge Volumes

Because the distribution of proposed project cost data is skewed, we report interquartile ranges to characterize the distribution of annual cost per recharge volume. We performed an exploratory analysis to understand how annual cost per volume ranges among:

1. All proposed projects,
2. Proposed projects grouped by goal (i.e., MAR is primary goal or ancillary goal),
3. Proposed projects grouped by specific funding opportunities (i.e., Propositions 1E, 13, 50 or 84), and
4. Proposed projects grouped by type of source water (i.e., surface water, stormwater, wastewater, or blend).

Because of the small sample size for actual cost and recharge volume data, we were not able to perform statistical analyses on the survey information. Instead, we plotted all data points for three categories of costs—O&M cost per annual recharge volume, capital cost per annual recharge volume, and total cost per annual recharge volume. Then, we compared these costs with the interquartile ranges for proposed O&M costs per annual recharge volume, capital

costs per annual recharge volume, and total costs per annual recharge volume for all projects with applications.

Geospatial Analysis

We performed an exploratory analysis to identify any geospatial trends by

1. Proposed project cost (i.e., proposed project cost in comparison to median cost of all proposed projects),
2. Proposed projects grouped by goal (i.e., MAR is primary goal or ancillary goal),
3. Proposed projects grouped by specific funding opportunities (i.e., Propositions 1E, 13, 50 or 84), and

4. Proposed projects grouped by type of source water (i.e., surface water, stormwater, wastewater, or blend).

RESULTS

Proposed Economic Costs per Recharge Volumes and Proposed Benefits

The median cost for all projects is \$410 per AFY (\$0.33 per m³ per year) (Figure 1A). Costs vary considerably, especially when analyzed by goal, funding opportunity, and source water (Figure 1B-1D). Median costs are about three times smaller (\$320 vs. \$830 per AFY [\$0.26 vs. \$0.67 per m³ per year]) when MAR is the primary goal of the project than when MAR is the ancillary goal. This trend is consistent with the cost analysis by

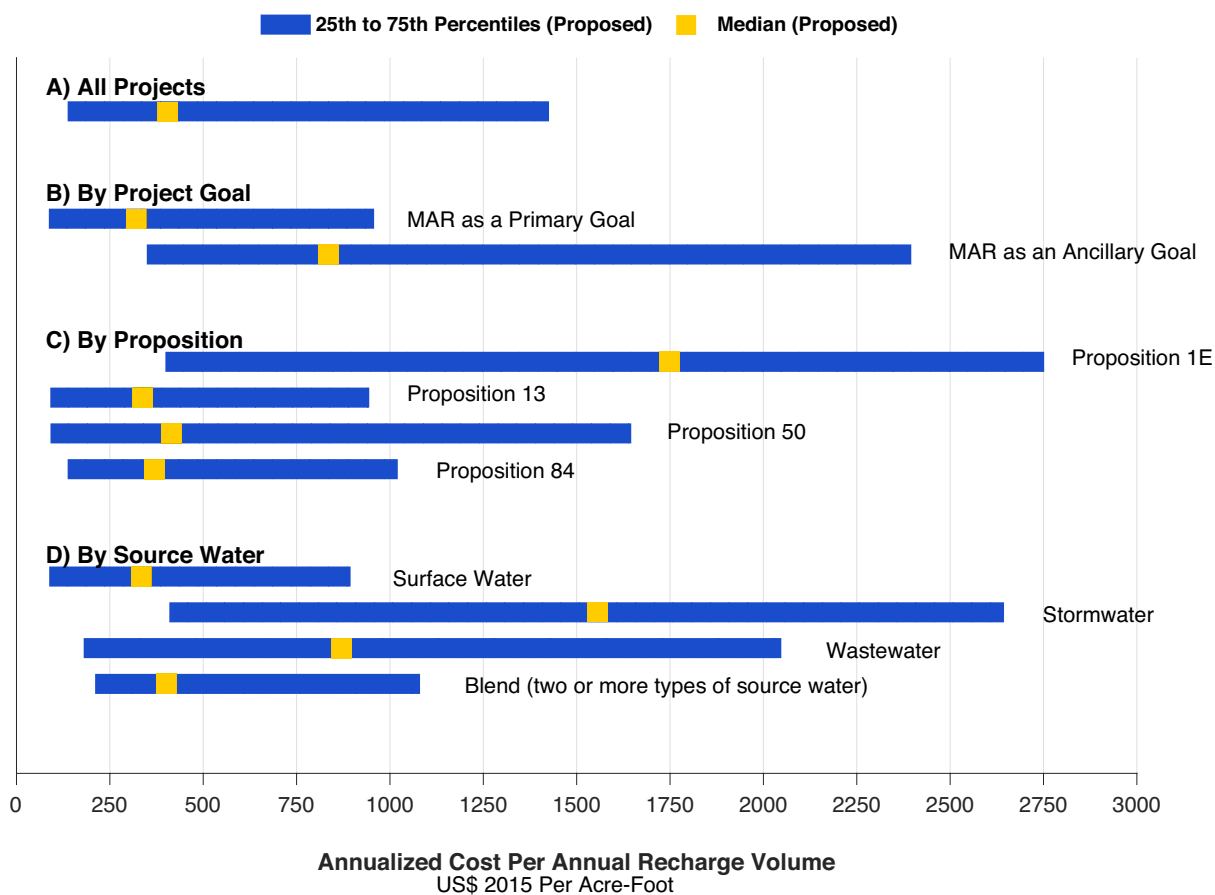


Figure 1 Interquartile ranges of MAR (annualized cost per annual recharge volume) for (A) all projects ($n_{all} = 106$); (B) by goal ($n_{Primary} = 66$, $n_{Ancillary} = 40$); (C) by proposition ($n_{1E} = 18$, $n_{13} = 39$, $n_{50} = 15$, $n_{84} = 34$); and (D) by source water ($n_{Surface} = 18$, $n_{Stormwater} = 39$, $n_{Wastewater} = 15$, $n_{Blend} = 34$). See Appendix B for detailed cost information in a table.

proposition. Proposition 13 projects, which focus primarily on MAR, have the lowest range and lowest median cost of all of the propositions' projects. The interquartile range and median for Proposition 1E projects are larger than the range and median for other propositions' projects. Stormwater and wastewater have larger interquartile ranges and medians than projects that use surface water or a blend of two or more types of source water.

Our exploratory analysis to identify geospatial trends by project cost (i.e., project cost in comparison to median of all projects), goal, funding opportunity, and source water indicates that there is a trend between some locations and the type of source water. Projects in the Central Valley primarily use surface water, while the urban coastal areas use a variety of source water types (Figure 2).

As noted earlier, using the 106 project proposals we identified 11 benefit categories. Increasing Water Supply, Conjunctive Use, and Flood Protection are the most common benefits reported (Figure 3). Almost half of all applications identify Increasing Water Supply or Conjunctive Use as benefits to their project, and the median costs for these applications are less than the median cost of all of the projects. Flood Protection is identified as a project benefit by one-third of the projects, but contrary to Increasing Water Supply or Conjunctive Use, the median cost for these projects is greater than the median cost of all of the projects.

Actual Economic Costs per Recharge Volumes and Factors that Promote and Limit Benefits

Actual Economic Costs per Recharge Volumes

Actual total costs have a large range. Some projects' actual total costs are outside of the proposed total cost interquartile range (Figure 4A). Some projects' capital costs fall within the interquartile range of proposed capital costs, but there are a few samples that have actual capital costs almost ten times the median of the proposed capital costs. (Figure 4B) Actual O&M costs fall within the interquartile range of proposed O&M costs (Figure 4C).

Factors Contributing to Differences in Proposed and Actual Costs and Proposed and Actual Recharge Volumes

Although some reported post-completion costs differ from their proposed costs (US\$ 2015), the survey indicates that there is no one consistent factor for these differences (i.e., reasons include adjusted contingency factors, changes in environmental compliance costs, changes in land costs, competitive construction bidding, and revised feasibility studies). Six respondents reported that the actual capital cost of their project is about equal to or less than the proposed capital cost, and seven respondents reported that the actual capital cost of their project exceeds the proposed cost. Only five of the 13 surveys provided actual annual O&M costs, and only three of these five had proposed O&M costs recorded in the proposition applications; all three of these projects' actual O&M costs are less than proposed O&M costs.

The actual and proposed average annual recharge volumes (AFY) are reported to be the same for three projects; the actual annual recharge volume (AFY) is reported to be less than the proposed annual recharge volumes (AFY) for six projects. The remaining projects did not provide responses. The survey indicates that the most important factor influencing whether the actual average annual recharge volume is less than the proposed average annual recharge volume is the availability of water for recharging and storing.

Project Benefits in Addition to Primary Project Benefit

Eighty percent of survey respondents highlight Increased Flexibility in Water Management and Increased Resilience to Drought and more than half of survey respondents highlight Enhanced Regional Self-Sufficiency as additional benefits to their project's primary goal.

Important Contributions to Achieving Primary Project Benefit

According to the survey responses, the two most important contributions (80% of respondents each) to the success of a MAR project are Financial Support and Good Communication with Stakeholders.

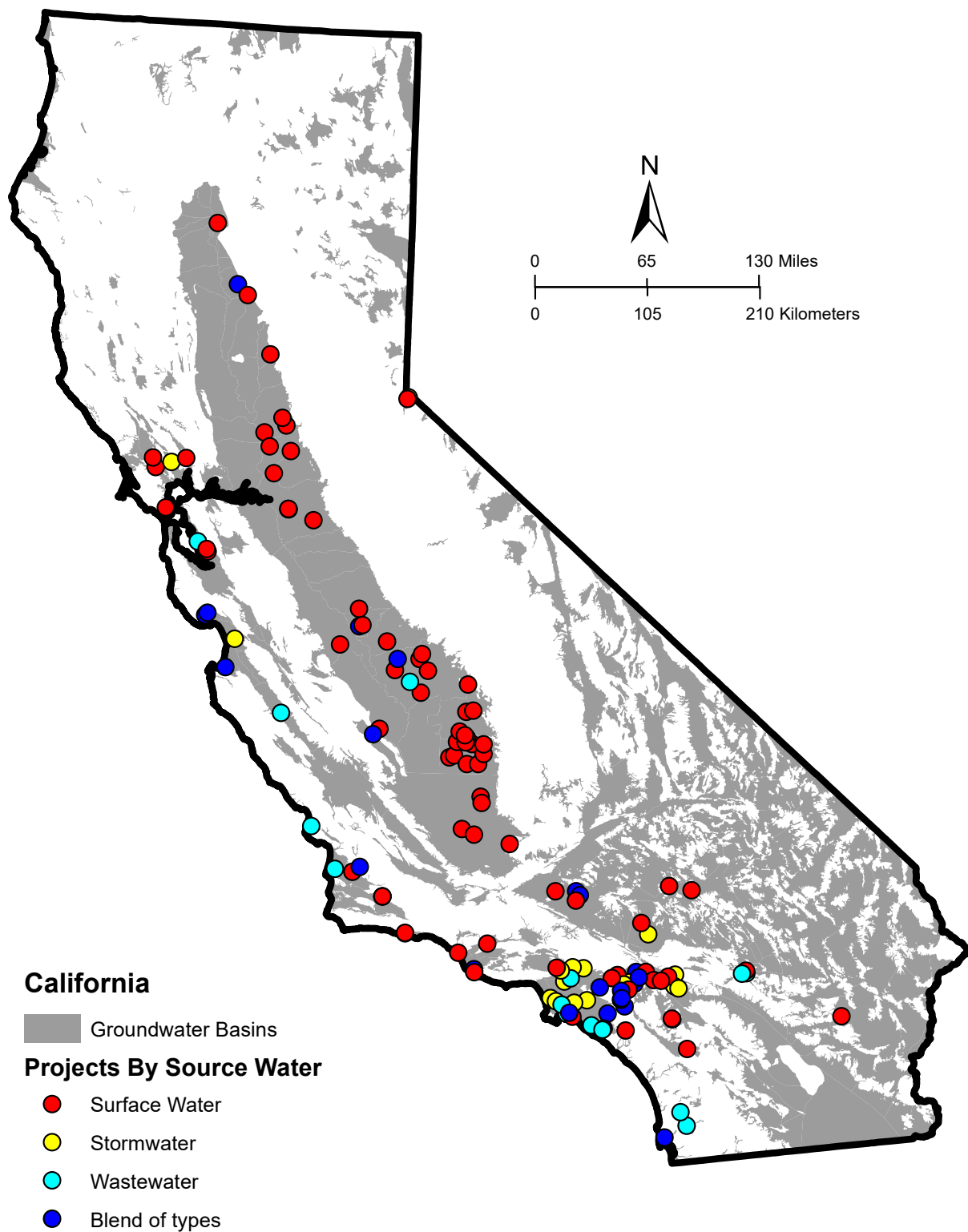


Figure 2 Geospatial representation of projects by source water

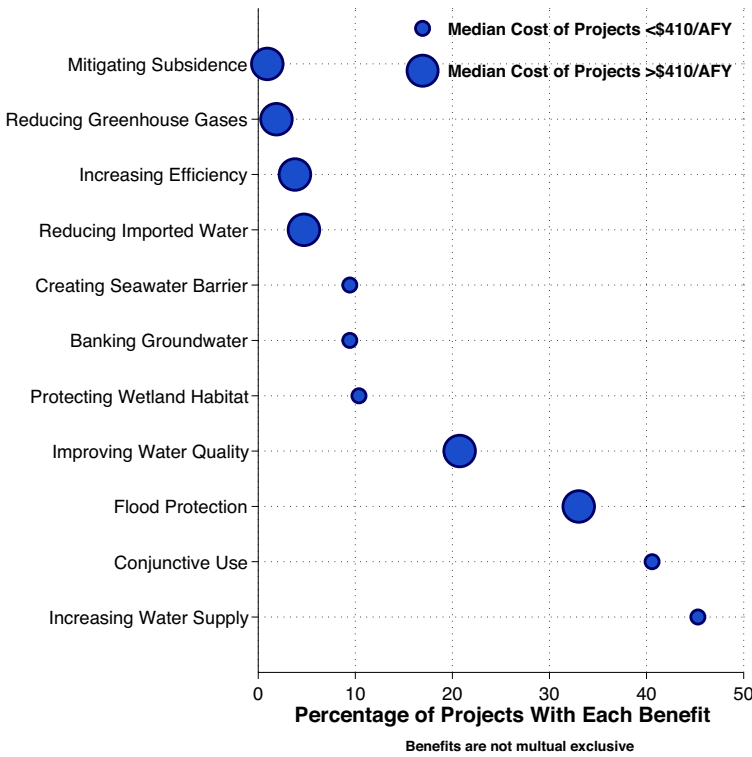


Figure 3 Analysis of project benefits with cost information. Projects were grouped into 11 benefit categories; projects that identified multiple benefits, were counted for each benefit identified (i.e., benefits are not mutually exclusive). The size of the dot indicates whether the median costs for projects within each benefit category is below or above the median cost of all of the projects (i.e., \$410 per AFY [\$0.33 per m³ per year]).

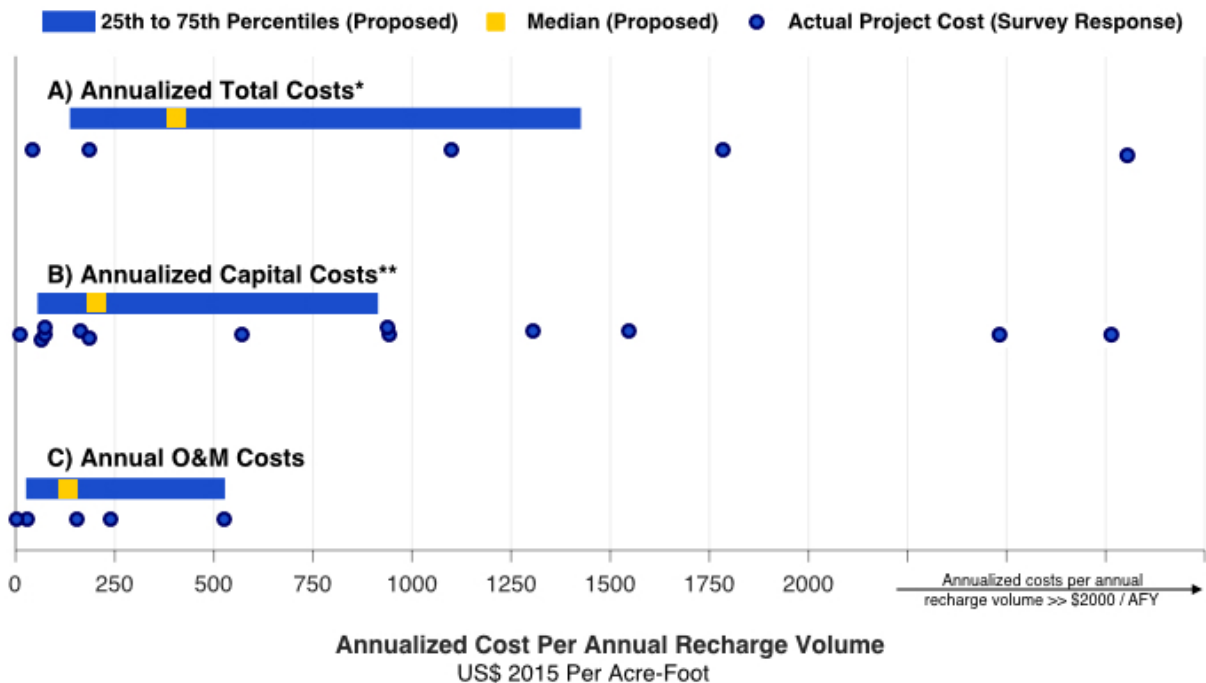


Figure 4 Comparison of proposed and actual (A) Annualized Total Costs* per Recharge Volumes ($n_{proposed}=106, n_{actual}=5$), (B) Annualized Capital Costs** per Recharge Volumes ($n_{proposed}=106, n_{actual}=13$), and (C) Annual O&M Costs per Recharge Volumes ($n_{proposed}=106, n_{actual}=5$). See Appendix B for detailed cost information in tabular form. *Only five of the 13 surveys provided actual O&M costs, so only five surveys were used to calculate actual total costs; annualized cost per recharge volume for far right point is above \$25,000. **Annualized costs per recharge volumes for far right points are close to or above \$20,000.

DISCUSSION

Proposed Economic Costs per Recharge Volumes and Proposed Benefits

The annualized proposed costs per recharge volume (US\$ 2015/AFY) of MAR projects vary considerably. We found that costs vary by project goals, funding proposition, and water source. Costs are higher when MAR is an ancillary rather than a primary goal of a project, but project outcomes are greater, too. Proposition applications indicate that communities are integrating MAR into flood control, stormwater management, wastewater recycling, water quality improvements, wildlife enhancement, and seawater intrusion prevention projects. This trend is nowhere more the case than within Proposition 1E (i.e., Disaster Preparedness and Flood Prevention Bond Act of 2006). The cost range for Proposition 1E projects is higher than for the other propositions, but this should not be surprising given that Proposition 1E projects also integrate elements of stormwater capture and flood management. Projects using stormwater as their water source have higher costs than projects using surface water, wastewater, or a blend (Figure 1D). Stormwater projects require more conveyance infrastructure than the other water sources; this can drive costs up, but it also provides the benefits associated with managing stormwater.

Our geospatial analysis indicates that stormwater projects and wastewater projects are scattered near urban areas and high population centers. This is not surprising, because urban areas have human-built impervious surfaces and higher populations than rural areas, which in turn result in larger quantities of stormwater runoff and wastewater effluent, respectively. Most projects in the Central Valley, on the other hand, use surface water primarily. Using stormwater and wastewater effluent as types of source water represents a mitigation of the effects of development and water use on groundwater recharge. The use of surface water as source water for groundwater recharge is closer to the traditional conjunctive use of surface and subsurface storage. These geospatial trends emphasize how MAR projects can allow agencies to tailor management to the local community's available resources, as well as the local community's needs.

Tailoring management to local community needs is a sentiment reiterated with the identification of 11 MAR project benefits from the proposition applications. Many of the benefits identified in the proposition applications are likely to become increasingly important as agencies struggle to adapt to changing climatic conditions and to meet the legislative requirements of SGMA. The increased competition for water among water users, combined with the threat of a changing climate, has presented significant challenges to securing reliable water sources and storage for diverse water needs.

Actual Economic Costs per Recharge Volumes and Factors that Promote and Limit Benefits

Actual Economic Costs per Recharge Volumes

A robust statistical analysis on actual costs for this study was not feasible because of the small sample size. Nevertheless, the interquartile range for proposed costs using all applications generally agrees with actual costs for completed projects (Figure 4). Our interquartile range for proposed costs using applications with MAR as a primary goal (\$80 to \$960 per AFY [\$0.06 to \$0.78 per m³ per year], with a median of \$320 per AFY [\$0.26 per m³ per year]) is comparable to a recent metadata analysis that compares low and high costs of conjunctive use and groundwater storage (\$10 to \$700 per AFY [\$0.01 to \$0.57 per m³ per year]) to other water supply opportunities for the state of California (Hanak et al. 2009).²

Factors Contributing to Differences in Proposed and Actual Costs and Proposed and Actual Recharge Volumes

The survey responses indicate that there are many reasons for differences between annualized proposed and actual costs (US\$ 2015), including revised feasibility studies, lack of data, adjusted contingency factors, changes in land costs, changes in environmental compliance costs, competitive construction bidding because of the

² Costs are converted into US\$ 2015 USD value using the 2009 Construction Cost Index published from *Engineering-News Record*, and costs were rounded to the nearest ten to match our data presentation. The report was published in 2009 and used \$10 per AFY as the low estimate and \$600 per AFY as the high estimate.

economic turndown, altered time lines, and design modifications resulting from public input (these reasons are not mutually exclusive). Alternatively, the survey indicates that there is one consistent factor that influences whether the actual AFY is less than the proposed average annual recharge volume (AFY): water source availability. Most of the respondents indicated that this was the result of inadequate funds to purchase water, inadequate access to water, or water source availability changes from the drought.

Although there are differences between proposed and actual costs per recharge volumes, the ranges for the proposed and actual costs per recharge volumes reported through the survey generally agree. Our results (Figure 4) are presented as annualized cost per annual recharge volume (US\$ 2015/AFY). Accordingly, the outlier points on the actual cost plot (Figure 4) can be a function of increased actual costs or decreased annual recharge volume. The survey responses indicate, however, that these outlier points are primarily a consequence of low groundwater recharge volumes. This is not surprising, because most of the projects we surveyed finished construction of the MAR facilities only recently and began operation during the beginning of the current drought.

Project Benefits in Addition to Primary Project Benefit

Over 80% of survey respondents highlighted Increased Flexibility in Water Management and Increased Resilience to Drought as additional benefits for their project, yet the most important factor contributing to the reduction in MAR recharge volumes was the limited availability of water during the current drought. The low rates of groundwater recharge are consistent with reduced water availability resulting from drought, but other factors influencing water access were highlighted in the survey as well. These include environmental permitting requirements and insufficient feasibility studies. This begs the question of whether drought is the limiting factor affecting water access. Once the severity of the drought is diminished, will projects still have trouble accessing water because of environmental permitting requirements, insufficient feasibility studies, or water rights permitting?

Important Contributions to Achieving Primary Project Benefit

In our survey, 80% of respondents with completed projects attributed the success of their project to Financial Support and Good Communication with Stakeholders. Local funding primarily supports water agencies and utilities in California, and this places an imbalance of financial pressure on small, rural water systems and makes it difficult to support a more integrated water management system (Hanak et al. 2014; Hanak et al. 2009). Rural regions are likely to find it difficult to raise adequate funds to support long-term, sustainable groundwater management using pumping fees alone, and may require state financial, technical, or other assistance to meet sustainability goals. Our analysis of proposition applications and funding indicates that state funding has played an important role in supporting MAR projects, and is likely to continue playing an important role as the state embraces SGMA and sustainably manages its groundwater.

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REFERENCES

- [CDWR] California Department of Water Resources. 2001. Groundwater storage program construction grant application. Sacramento, California. Sacramento (CA): California Department of Water Resources.
- [CDWR] California Department of Water Resources. 2003. California's groundwater: Bulletin 118. Sacramento (CA): California Department of Water Resources. [accessed 2015 Aug 15]. Available from: http://www.water.ca.gov/groundwater/bulletin118/update_2003.cfm.

- [CDWR] California Department of Water Resources. 2013. North-of-the-Delta offshore storage preliminary engineering design and cost estimate. Sacramento (CA): California Department of Water Resources. [accessed 2015 Aug 15]. Available from: http://www.water.ca.gov/storage/northdelta/prelim_admin_draft_EngineeringDesign_index.cfm
- [CDWR] California Department of Water Resources. 2014a. California groundwater elevation monitoring: basin prioritization process. Sacramento (CA): California Department of Water Resources. [accessed 2015 Aug 15]. Available from: http://www.water.ca.gov/groundwater/casgem/pdfs/CA_GW%20Basin%20Prioritization_07-10-14.pdf
- [CDWR] California Department of Water Resources. 2014b. Public update for drought response: groundwater basins with potential water shortages and gaps in groundwater monitoring. Sacramento (CA): California Department of Water Resources, Drought Management Operations Center. [accessed 2015 Aug 15]. Available from: http://www.water.ca.gov/waterconditions/docs/DWR_PublicUpdateforDroughtResponse_GroundwaterBasins.pdf
- [CDWR] California Department of Water Resources. 2015a. California's most significant droughts: comparing historical and recent conditions. Sacramento (CA): California Department of Water Resources. [accessed 2015 Aug 15]. Available from: http://www.water.ca.gov/waterconditions/docs/California_Significant_Droughts_2015_small.pdf
- [CDWR] California Department of Water Resources. 2015b. Groundwater sustainability program: draft strategic plan. Sacramento (CA): California Department of Water Resources. [accessed 2015 Aug 15]. Available from: http://www.water.ca.gov/groundwater/sgm/pdfs/DWR_GSP_DraftStrategicPlanMarch2015.pdf
- Famiglietti JS, Lo M, Ho SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, Linage CRD, Rodell M. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophys Res Lett* 38(3). doi: <http://dx.doi.org/10.1029/2010GL046442>.
- Faunt CC. 2009. Groundwater availability of the Central Valley Aquifer, California. Reston (VA): U.S. Geological Survey.
- Groundwater: Conjunctive use. 2015c. Sacramento (CA): California Department of Water Resources. [updated 2016 Jun 06; accessed 2015 Sep 11]. <http://www.cd.water.ca.gov/groundwater/conjunctiveuse.cfm>
- Hanak E, Lund J, Dinar A, Gray B, Howitt R, Mount J, Moyle P, Thompson BB. 2009. California water myths. [accessed 2015 Aug 15]. San Francisco (CA): Public Policy Institute of California. Available from: http://www.ppic.org/content/pubs/report/R_1209EHR.pdf
- Hanak E, Gray B, Lund J, Mitchell D, Chappelle C, Fahlund A, Jessoe K, Medellín-Azuara J, Misczynski D, Nachbaur J, et al. 2014. Paying for water in California. [accessed 2015 Aug 15]. San Francisco (CA): Public Policy Institute of California. Available from: http://www.ppic.org/content/pubs/report/R_314EHR.pdf
- Nelson RL. 2012. Assessing local planning to control groundwater depletion: California as a microcosm of global issues. *Water Resour Res* 48. doi: <http://dx.doi.org/10.1029/2011WR010927>.
- [USBR] U.S. Bureau of Reclamation. 2008. Plan formulation report: upper San Joaquin River basin storage investigation. Sacramento (CA): U.S. Bureau of Reclamation. [accessed 2015 Aug 15]. Available from: http://www.usbr.gov/mp/scca/storage/docs/usjrbsi_pfr/ch0_summary.pdf
- [USBR] U.S. Bureau of Reclamation. 2011. Shasta Lake water resources investigation. Draft feasibility report. Sacramento (CA): U.S. Bureau of Reclamation. [accessed 2015 Aug 15]. Available from: http://www.usbr.gov/mp/slwri/docs/DFR/MP700_SLWRI_001_ChESto3_DFR.pdf
- [USBR] U.S. Bureau of Reclamation. 2014. Upper San Joaquin River basin storage investigation. Draft feasibility report. Sacramento (CA): U.S. Bureau of Reclamation. [accessed 2015 Aug 15]. Available from: http://www.usbr.gov/mp/scca/storage/docs/Draft_Feasibility_Report_2014/USJRBSI_Draft_FR_2014_Full_Report.pdf
- [WEF] Water Education Foundation. 2015. The 2014 sustainable groundwater management act: a handbook to understanding and implementing the law. Sacramento (CA): WEF.